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13. ABSTRACT (Maximum 200 words)

This is the sixth and final report composed under Contract DAAD19-02-C-0088 for STTR Topic ARMY02-T002. This STTR Phase I effort entailed two separate tasks, each focusing on a different aspect of the bioparticle remote detection problem: (1) the phenomenology of absorption by Bacillus subtillis in the THz region between 300 and 500 GHz, and (2) the design, construction, and table-top demonstration of a differential-absorption radar (DAR) transceiver suitable as a remote sensor in Phase II. Both tasks met with significant success. The primary objective of the phenomenology effort was to measure the THz transmission through BG with the highest possible accuracy using a vector network analyzer. Previously, measurements made at the University of Virginia displayed two possible absorption resonances in this region centered at 327 and 421 GHz, respectively. In our Phase I measurements, there was *no evidence* for the 327 GHz resonance. But there was distinct evidence for the 421 GHz resonance that appeared both in vector-network-analyzer and in differential-absorption-radar measurements. In fact, two promising signatures were observed in the Phase I effort – one around 425 GHz and the other around 445 GHz. These are discussed further in the attached document.

The primary objective of the transceiver development effort was to construct and show the feasibility of a differential absorption radar operating between roughly 420 and 450 GHz. To meet the requirement of field portability, an all-solid-state, cryogen-free, transceiver was assembled using a harmonic multiplier chain for the transmitter and a hot electron bolometer for the receiver. The hot electron bolometer is operated at 4.2 K in a compact closed-cycle refrigerator described in detail on the attached document.

In the first bench-top DAR demonstration, the BG absorption signature centered around 425 GHz was detected and shown to have curvature very close to that obtained by vector network analysis. *This is considered to represent a proof-of-concept for the proposed biparticle DAR approach*. The details are provided in the attached document.

14. SUBJECT TERMS
THz, absorption signature, remote detection, radar, bioparticle , STTR Report

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A. THz Phenomenology

A.1. BG Sample Preparation

Bacillus Subtillis (BG) is an innocuous rodlike bacterium that serves as a surrogate for Bacillus Antracis, or Anthrax. Both bacteria reproduce by creating spores within their cell bodies, called endospores. It is the endospores of Anthrax that pose the biological threat to human beings and so are interesting to BWD technology. The endospores of BG are similar to those of Anthrax in size and shape. They can be approximated as prolate spheroids having a length between 1.5 and 1.8 micron and a width of approximately 0.8 micron. They are composed primarily of protein and have a shell made of peptidoglycan, which is similar materially to keratin. The shell is also rich in calcium through the chemical dipicolinic acid.

Two types of BG spore samples were prepared for the Phase I effort through the expert support of Dr. Alan Samuels of the US Army SBCCOM. The first sample was the BG film embedded in a Goretex membrane (Spectratech film card), henceforth called a "BG-Goretex card." Being a fibrous form of PTFE, Goretex is very transparent in the millimeter-wave and THz regions. A photograph of a typical BG card is shown in Fig. 1(b). The second sample was a relatively large amount of BG powder (0.492 gm) loaded into a special vial provided by Peter Siegel of JPL. A picture of this vial is shown in Fig. 1(a). It holds the BG in a cylindrical hole one cm in diameter and 0.635 cm thick between two 10-micron thick polyethylene windows.

A.2. THz Attenuation Measurements: 300-370 GHz

To obtain the most accurate possible measurements of the propagation of THz radiation through BG spores, the Phase I investigators used an experimental set-up based on a vector network analyzer (VNA). The VNA is a commercially-available instrument from AB MM-Wave in France. Its functionality is based on phase locking a Gunn diode that generates the desired radiation by harmonic-multiplication. Although it provides two-port S-parameters up to roughly 500 GHz, its tunability is but a few GHz per harmonic and its dynamic range is far below the HP (now Agilent) 8510 series VNAs popular at frequencies below 100 GHz. Nevertheless, the AB is probably the most accurate commercial instrument in this frequency range.

Starting in late November 2002 the researchers began transmission experiments between 300 and 370 GHz using the set-up shown in Fig. 2. In one measurement, six of the BG-Goretex cards were stacked in series to enhance any absorption signatures compared to those of a single card. The experimental results are shown in Fig. 3 along with a vertical red line marking the frequency where an absorption signature may have occurred in single-card measurements at 327 GHz. Clearly, there are no obvious signatures at around 327 GHz. In fact there are no absorption signatures anywhere between 300 and 370 GHz. At first we thought that there may be a new signature centered around 340 GHz (black sub-spectrum in Fig. 3). But a careful re-measurement yielded the pastel blue curve in which no absorption signature is present. So we conclude from the six-card measurements that there are no significant absorption resonances in the BG-Goretex cards between 300 and 370 GHz

The absorption between 300 and 370 GHz was addressed with more confidence using the BG-vial shown in Fig. 1(a). The experimental results are shown in Fig. 4 with a course (top) and fine (bottom) absorption scale. As expected, the net insertion loss of the sample is much higher

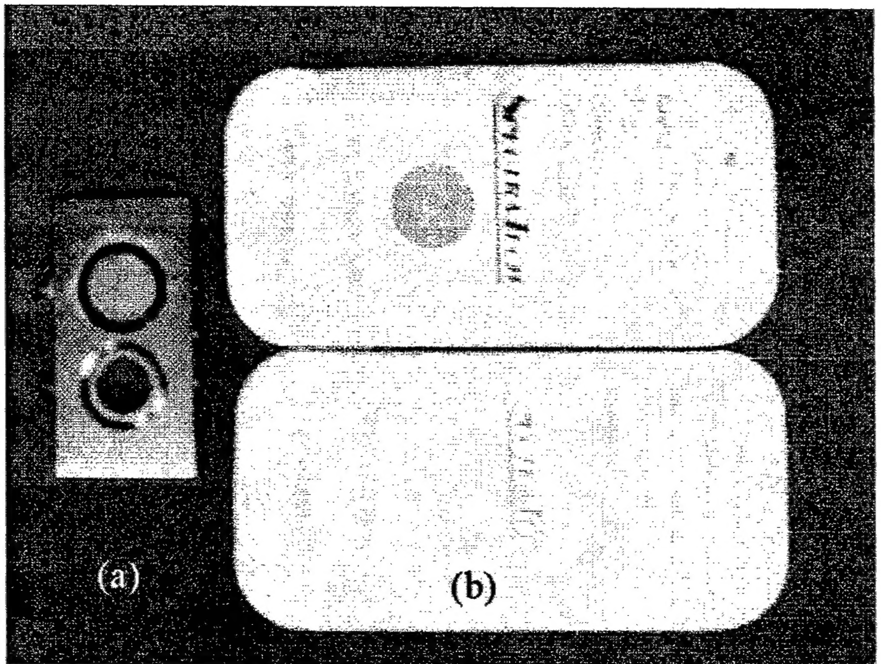

Fig. 1. (a) Photograph of special sample holder (Vial) for BG material containing two cylindrical holes, the top one (Sample hole) containing the BG material and the bottom one (Reference hole) containing air or Teflon. Both have two thin (10 micron) polyethylene windows. (b) Photograph of BG-Goretex cards showing a round aperture in a SpectraTech cardboard Sample Card. The top photo shows the Goretex-embedded sample (Sample card) and the bottom one shows the Goretex alone (Reference card).

than the six BG-Goretex cards because of the much greater optical depth. It starts at about 5.8 dB at 300 GHz, is rather flat to about 342 GHz and then starts to increase rapidly to about 7.2 dB at 370 GHz. We believe that this rapid increase is associated with an approach to a resonant absorption band centered above 400 GHz (see discussion below). But more importantly, Fig. 4 reinforces our conclusion from the six-card measurements that *there are no significant absorption resonances* at any other frequency between 300 and 370 GHz.

A.3. THz Attenuation Measurements: 400-450 GHz

Starting in December 2002 experimental AB-VNA transmission experiments were conducted between 400 and 475 GHz on the BG-Goretex and BG-vial samples shown in Fig. 1. In one measurement, six of the BG-Goretex cards were stacked in series to enhance any absorption signatures compared to those of a single card. The experimental data is shown in Fig. 5. The bottom graph in Fig. 5 is the transmission through the BG-Goretex films normalized with respect to the transmission through the "reference" sample of Goretex films alone. The dominant feature in the normalized transmission spectrum is a broad attenuation that starts at 0.8 dB at 400 GHz and increases gradually to about 1.1 dB at 475 GHz. A possible absorption resonance is apparent from the transmission dip around 418 GHz. But its depth is only about 0.3 dB, and it

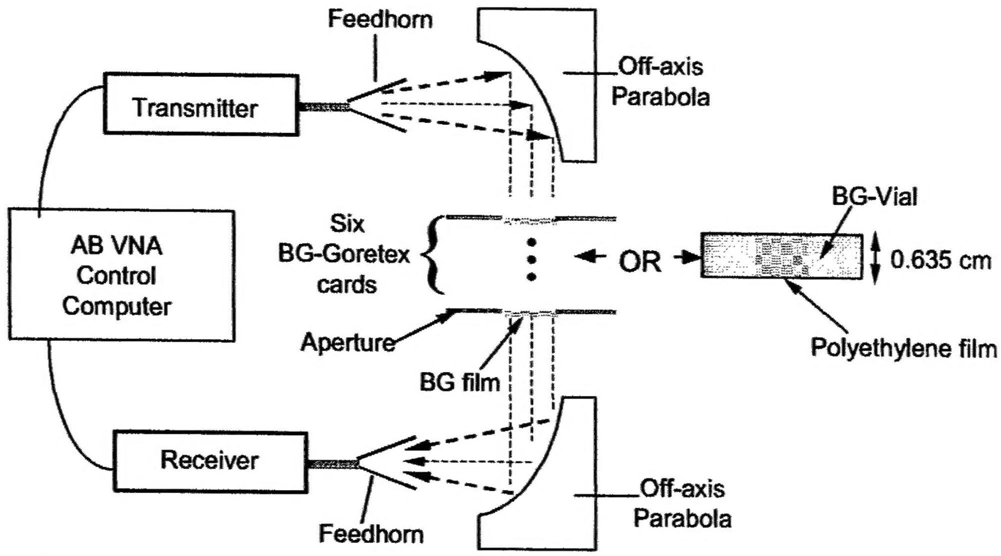

Fig. 2. Transmission measurement set-up for two samples: (1) six BG-film-on-Goretex membranes, and (2) BG-filled or Teflon-filled vial.

corresponds to a similar dip in the transmission through the Goretex films alone. So we are not confident that this is a real absorption resonance. Above 425 GHz, any feature in the normalized transmission through the BG-Goretex films is too weak to believe there are significant absorption resonances in this range.

Thanks to the availability of the BG-vial sample, we were able to measure the absorption between 400 and 475 GHz with greater confidence than allowed by the BG-Goretex films. The experimental results are shown in Fig. 6. The bottom curve is the transmission through the vial filled with BG powder, and the middle "reference" curve is the transmission through the same vial filled with Teflon. The most apparent attenuation feature in the BG-filled vial curve is the dip centered around 445 GHz, which is roughly 4 dB deep. But this feature also occurs in the reference spectrum, although the latter is less than 1 dB deep. A more promising attenuation feature occurs between approximately 425 and 430 GHz. Although this feature is only about 2 dB deep, there is no corresponding feature in the "reference" spectrum. Furthermore, it coincides in frequency with a signature seen earlier around 421 GHz by Dr. T. Globus and colleagues at the University of Virginia. The Virginia measurements were carried out by Fourier transform spectroscopy at a far courser resolution than that applied here. So the 425-GHz feature is the most promising sign of a real resonant absorption signature that we have seen in any BG sample to date.

Bacillus subtilis Impregnated Gore-Tex Cards: 5mg/card, six card stack. Aperture=1cm

Data collected Dec.10, 2002. Peter Siegel, JPL.

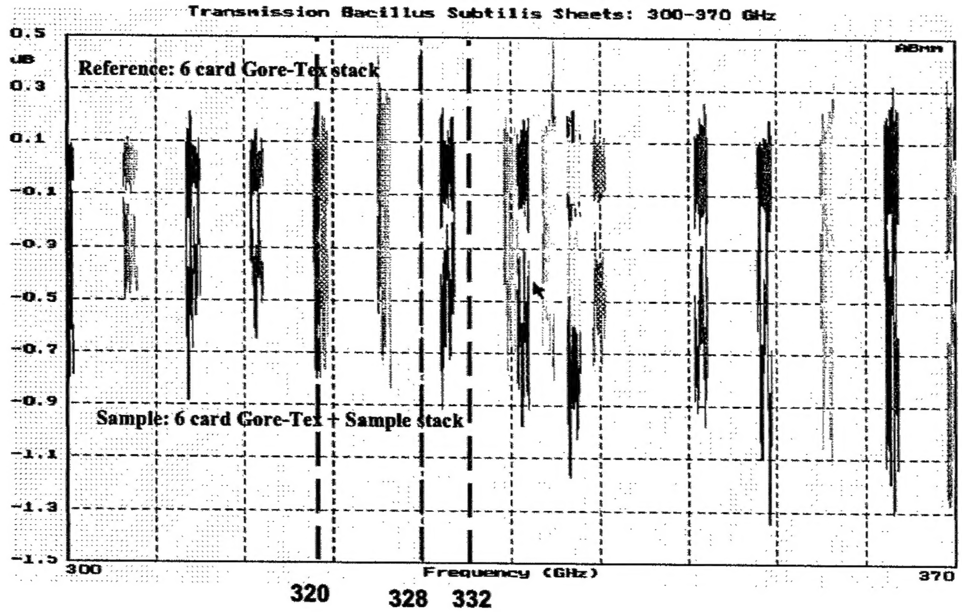

Fig. 3. Transmission spectra for stack of six BG-Goretex films (Sample) and stack of six Goretex films alone (Reference). The red vertical dashed line (327 GHz) represents the frequency where an absorption resonance may have been observed in BG samples at the University of Virginia by Fourier transform spectroscopy.

Bacillus subtilis Powder: 215mg, Volume=0.492cc, path length =0.635cm, Aperture=1cm
Data collected Dec. 9, 2002. Peter Siegel, JPL.

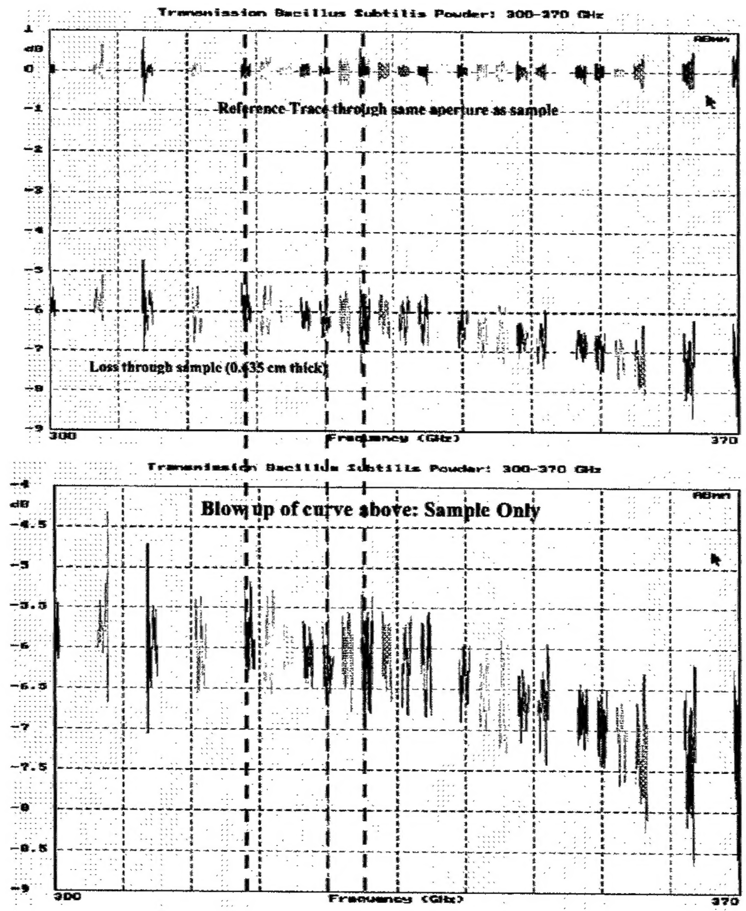

Fig. 4. Experimental transmission through the BG vial shown in Fig. 1(a). The top curve has a course vertical scale (10 dB total) and the bottom plot a finer scale (5 dB total). Each spectrum is normalized to transmission through the same vial without BG material in it.

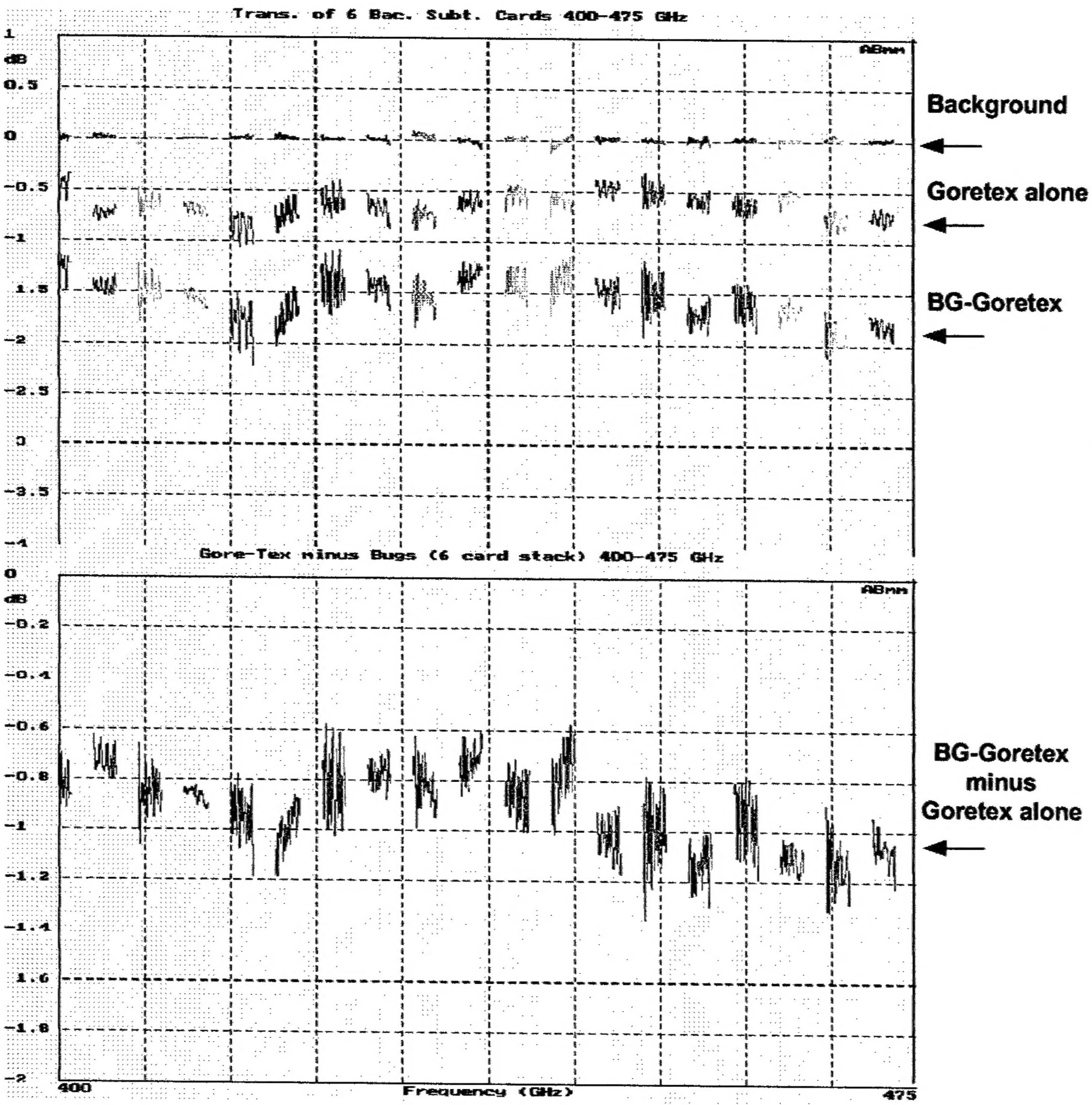

Fig. 5. Top graph: transmission spectra through stack of six BG-Goretex films, stack of six Goretex films alone, and sample holder alone ("Background"). Bottom graph: the computed difference between the BG-Goretex spectrum and the Goretex-alone spectrum.

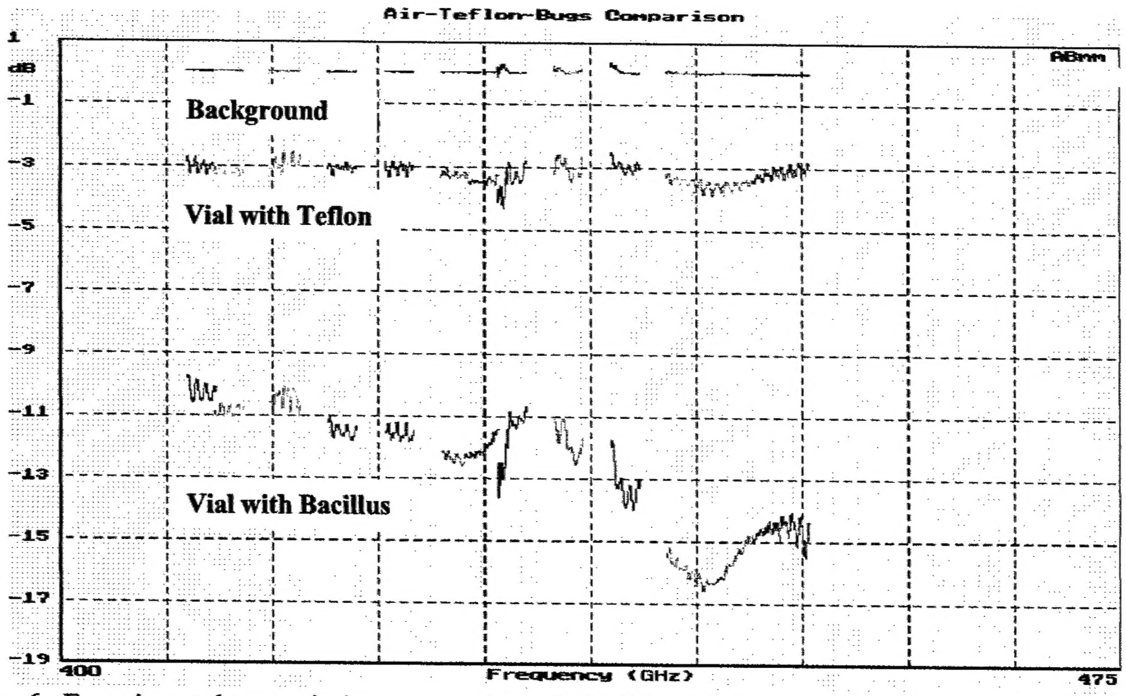

Fig. 6. Experimental transmission spectra through the BG vial shown in Fig. 1(a). The bottom curve shows the transmission with BG power filling the vial. The middle curve shows the transmission with Teflon filling the vial. The top curve shows the transmission through free space with no vial present.

B. DAR Transceiver Development

The chosen radar system architecture for this STTR is the incoherent system of Fig. 7. A cw signal is sent out by the transmitter, passes through the bioparticle sample, and is collected by the receiver. The first electronic component in the receiver is the "direct" detector that rectifies the radiation from the ~400 GHz region to baseband. Our direct detector is a bolometer and the baseband is defined by amplitude or frequency modulation in the transmitter to avoid gain drifts in the THz electronics that occur near dc. For AM modulation, the synchronous detection is carried out using a lock-in amplifier. The important performance characteristics for this, or any practical remote sensor, are the signal-to-noise ratio SNR, the probability of detection Pd, and the probability of false-alarm Pfa after down-conversion to dc. All of these have been analyzed and found to be satisfactory for many remote sensor applications. The analysis was carried out under a separate DoD sponsored effort and the details are explained elsewhere.[1]

B.1. DAR Transmitter

Recent progress on the development of all-electronically-tuned solid-state local oscillator sources for THz heterodyne spectroscopy applications[2] has enabled the deployment of mW level transmitters for this STTR program. These transmitters use commercially available microwave components (Ka band [22-33 GHz] synthesizers, or YIG tuned oscillators) coupled with active

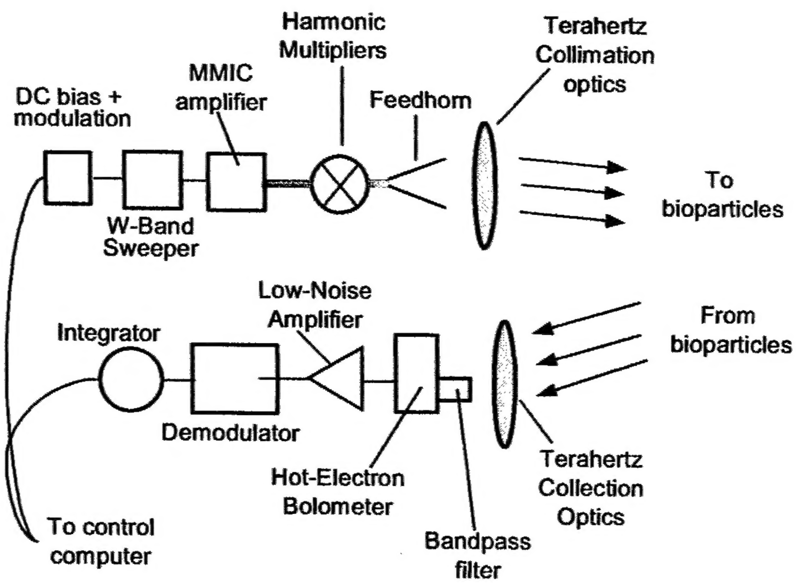

Fig. 7. Block diagram of bench-top differential-absorption radar demonstrated in Phase-I effort

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[1] "Remote Detection of Bioparticles in the THz Region," E.R. Brown, D.L. Woolard, A.C. Samuels, T. Globus, and B. Gelmont, presented at the 2002 International Microwave Symposium, Seattle, WA.

W-band [75-110 GHz] upconverters (usually a doubler to U band [40-60 GHz] followed by an amplifier and another doubler to W band). At W band, custom power amplifier modules using GaAs MMIC technology are used to increase the available power to 200-300 mW. Broadband fix-tuned custom JPL fabricated planar Schottky diode frequency multipliers (doublers or triplers) can then be employed to produce power in the THz bands. Transmitter chains using this technology have been designed, fabricated, assembled and tested at JPL at frequencies as high as 1600 GHz. At 400 GHz these sources have produced more than 10 mW of peak output power and more than 5mW over a 10% bandwidth. A block diagram of a sample chain for an output at 410-430 GHz is shown in Fig. 8. A picture of the actual hardware is shown in Fig. 9.

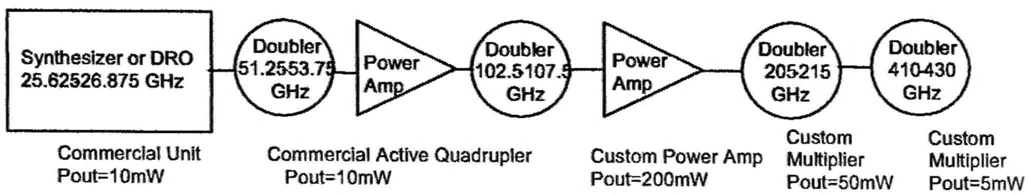

Fig. 8 . Block diagram of proposed electronically tuned transmitter based on a synthesized source followed by solid-state amplifiers and frequency doublers. Demonstrated output power is >5mW at 420 GHz.

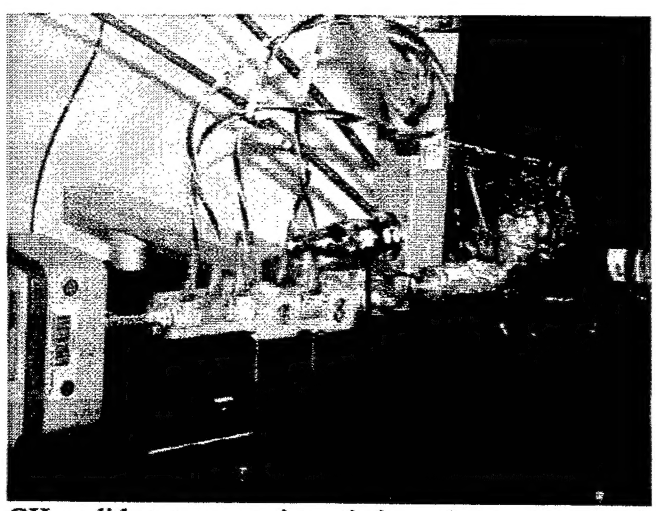

Fig. 9. Picture of 425 GHz solid-state transmitter chain as demonstrated in Phase I effort

[2] I. Mehdi, E. Schlecht, G. Chattopadhyay and Peter H. Siegel, "THz Local Oscillator Sources," Far-IR, Sub-mm & mm Detector Tech. Workshop, Monterey, CA, March 2002.

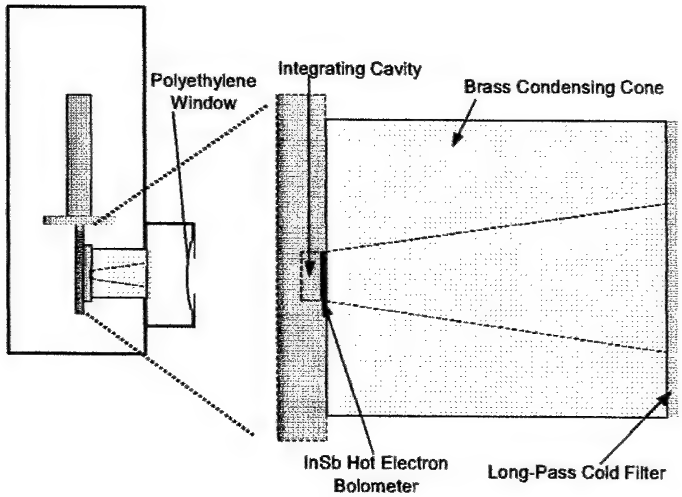

Fig. 10. Cross-sectional view of InSb hot-electron bolometer and brass feedhorn/condensing cone mounted on Gifford-McMahon refrigerator cold finger.

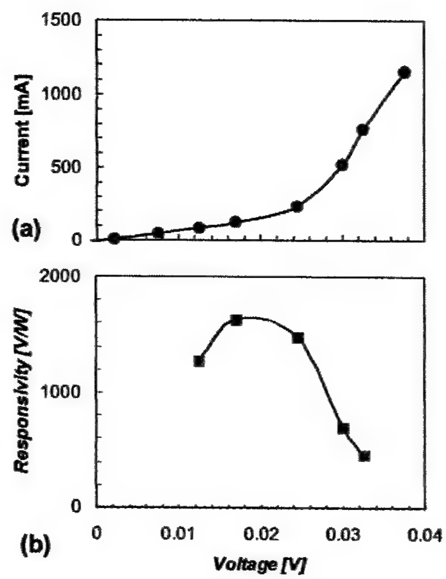

Fig. 11. (a) Experimental current-voltage curve of InSb hot electron bolometer at 3.5 K. (b) Electrical responsivity derived from current-voltage curve.

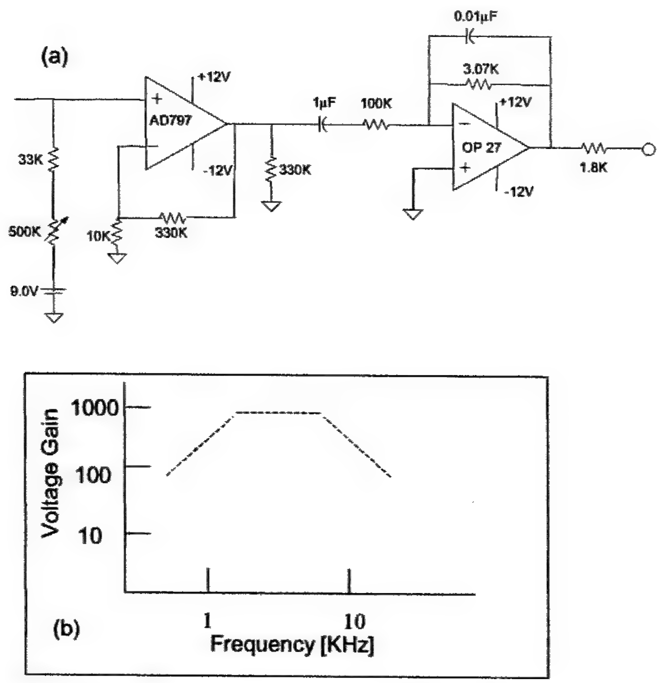

Fig. 12. (a) Schematic diagram of room-temperature low-noise amplifier that couples signal from InSb HEB. (b) Gain vs frequency for low-noise amplifier.

B.2. DAR Receiver

As shown in Fig. 7 the receiver is designed for direct detection of a coherent (radar) signal provided by a tunable transmitter operating in this frequency region. After considerable investigation in Phase I, the detector element chosen for the receiver was an InSb hot electron bolometer (HEB) made by the principal investigator. The HEB consists of a rod of highly pure and compensated InSb mounted across a circular waveguide. The diameter of the oxygen-free copper waveguide is 0.090 inch corresponding to a cutoff frequency of the fundamental TE_{11} mode of 78 GHz. As shown in Fig. 10, the HEB is mounted at the throat of a brass conical feedhorn having a flare angle of 7.5 and a length of 0.75 inch. At frequencies for which the feedhorn is unimodal, the antenna pattern of the feedhorn is asymmetric in the E and H planes but has small enough sidelobes to be useful. As the frequency approaches 425 GHz, the feedhorn becomes highly overmoded but the antenna pattern remains useful if the detector couples roughly equally to all of the modes.

The performance of the InSb hot-electron bolometer and associated elecronics is summarized in Figs. 11 and 12. As plotted in Fig. 11, the peak electrical responsivity is just over 1600 V/W, and the electrical NEP is about $8x10^{-13}$ W/Hz$^{1/2}$ when operating at 3.5 K. This is about three orders of magnitude more sensitive than the best room-temperature THz bolometers (e..g., Golay cells). To maintain this electrical NEP without serious degradation, the bolometer must be coupled to a very-low-noise amplifier, as shown schematically in Fig. 12. Fortunately,

certain operational amplifiers generate noise voltages of approximately 1 nV/Hz $^{1/2}$. The Analog-Devices 797 is an example, and is used as the first stage of the low-noise amplifier in the present DAR receiver.

The HEB and feedhorn assembly is mounted on the cold finger of a two-stage Gifford-McMahon refrigerator as shown in Fig. 13. Developments in Japan (Sumitomo Heavy Industries) have popularized GM refrigerators because of their low cost, superior reliability, and small size. The refrigerator for our receiver, distributed by Janis Research, is the smallest of the G-M variety, and dissipates a maximum power of only 0.1 W. Although this seems low, the HEB bolometer only dissipates a small fraction of this and its low output impedance allows for a room-temperature preamplifier rather than a cryogenic one. The size and weight of the refrigerator are small enough that it could, in principle be taken into the field and operated from a standard 2-3-KW portable electrical generator.

With HEB bias and radiative loading, the cold-finger temperature readily drops to about 3.5 K and maintains this temperature for any required time up to the maintainance-free lifetime of about 10,000 hours. The only undesirable effect of the GM operation is the ~0.1 K spike with each compressional stroke. This is a good reason for using a semiconducting (InSb) hot electron bolometer rather than other possible bolometers based on semiconductors or superconductors. Superconducting bolometers, such as those made from niobium bridges, display the critical phenomena that causes a large spurious response to even small temperature spikes around 4 K base temperature. With InSb, the spikes only cause a small change in responsivity that is readily averaged out by post-detection signal processing.

C. <u>DAR Transceiver Integration and Demonstration</u>

By the end of the Phase I effort the transmitter and receiver had been separately characterized and were ready for integration and demonstration. The first integration experiment is shown pictorially in Fig. 13, carried out at JPL in the laboratory of Dr. Peter Siegel. The components are labeled in the figure. Time did not permit the optimization of the solid-state transmitter power, but it immediately produced the power spectrum shown in Fig. 14. This proved enough to complete the Phase-I effort.

In the limited time of Phase I we had time only for a few experiments, one of which was particularly successful. We were able to operate the transceiver in differential mode by frequency hopping at a rate of 1 KHz between 420, 425, and 430 GHz. Two samples were placed in the transmitter-to-receiver path: (1) a Teflon control sample, and (2) the BG vial discussed above. Upon normalizing the BG data to the Teflon background signature, we obtained the blue points shown in Fig. 15. They are superimposed on the vector network analyzer (VNA) data obtained on the same sample. Notice that the three points are at approximately the same attenuation level and follow approximately the same curvature as the VNA data. So we take this as the first successful demonstration of the DAR approach.

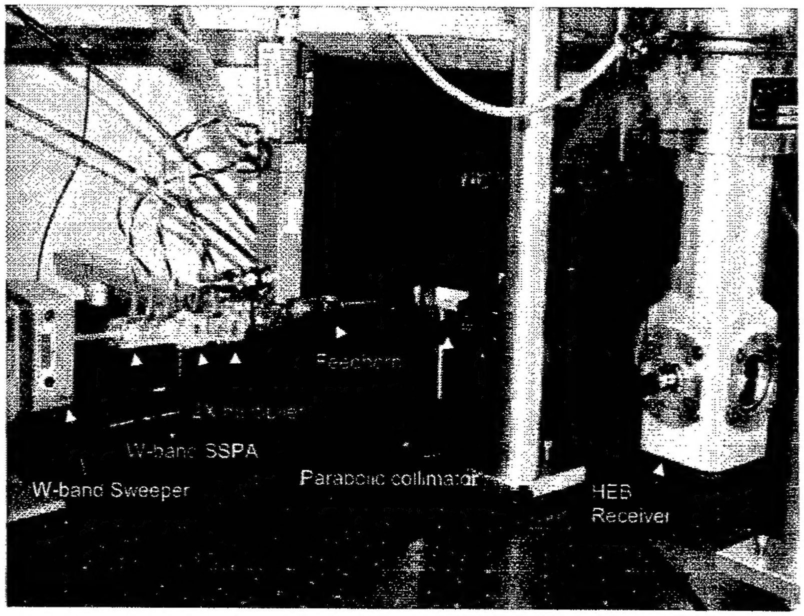

Fig. 13. Integration of 425-GHz solid-state transmitter and hot-electron bolometer (HEB) receiver developed under the Phase I effort.

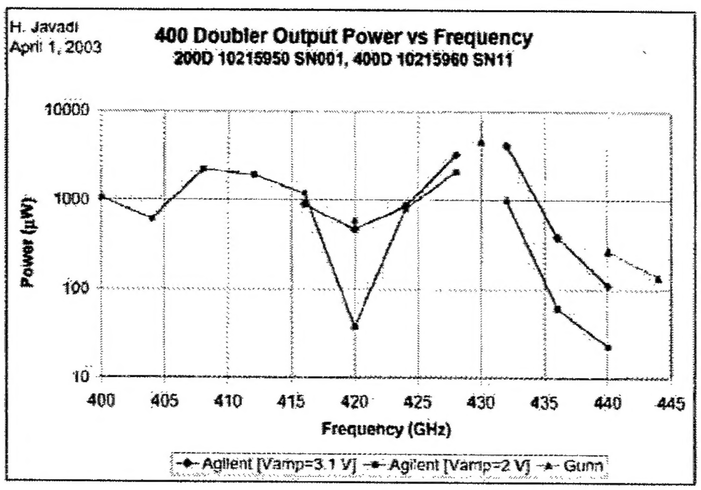

Fig. 14. Output power vs frequency for the solid-state transmitter from the Phase I effort

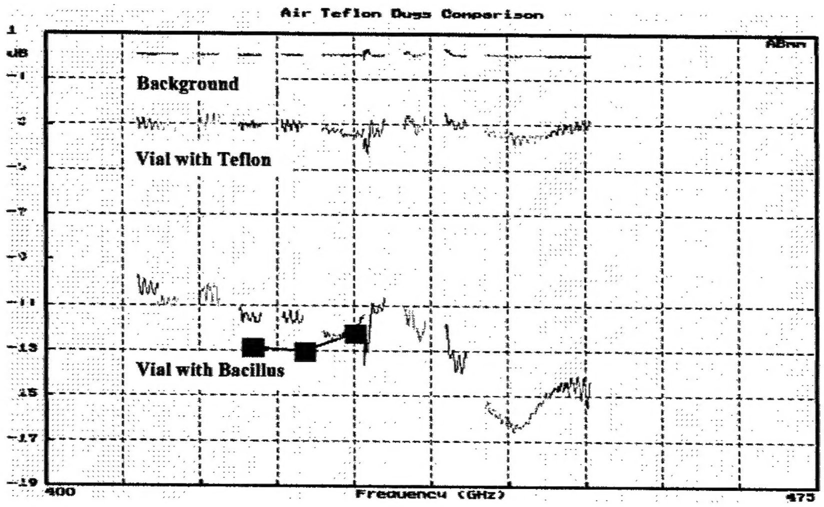

Fig. 15. First experimental results (blue points) for the Phase I transceiver components operating in differential absorption mode between 420, 425, and 430 GHz on the BG-vial sample.

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